1 FROM MILLIARCSECONDS TO MICROARCSECONDS

Astrometry is the foundation on which almost all of astronomy is based. Currently, we have accurate distances — via parallaxes — to stars only in our local Galactic neighborhood of the disk, but SIM will extend our reach throughout the Galaxy. From the largest astronomical scales to the smallest, the Space Interferometry Mission will contribute to the cutting edge of astronomical research.

The nearby star-forming regions in the Orion nebula are potential targets for SIM. Image: 2MASS near-infrared sky survey.

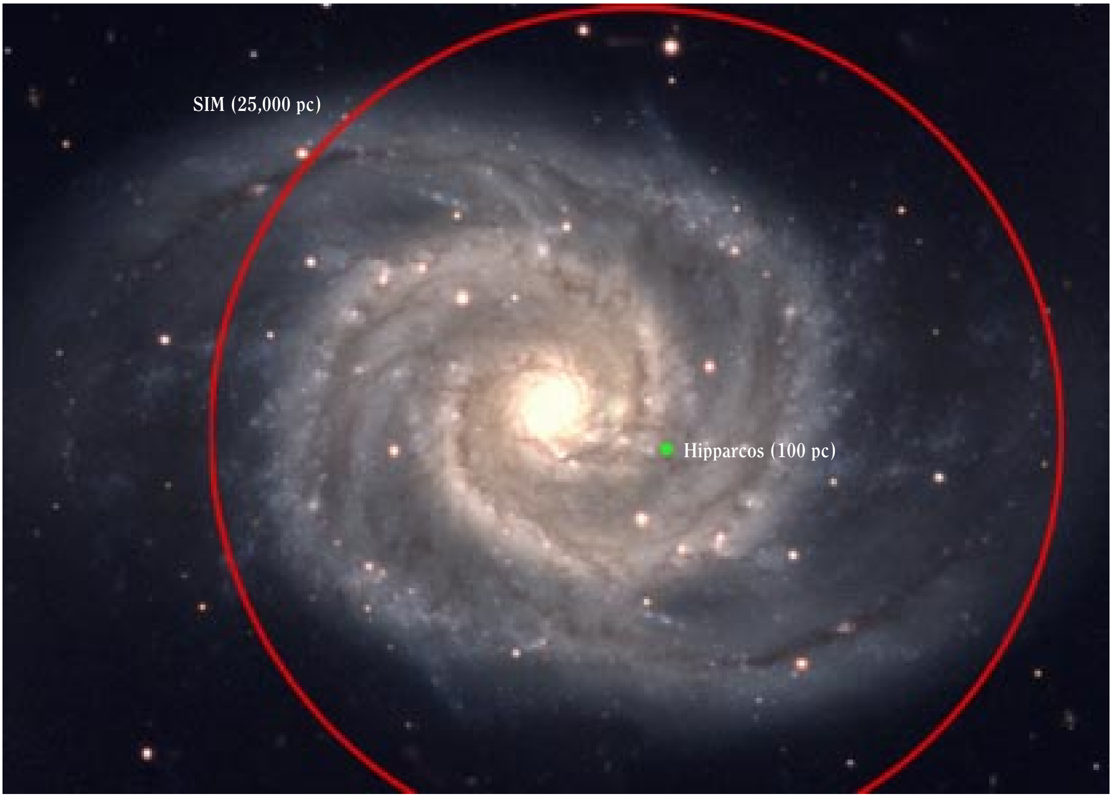
SIM will operate as an observatory, performing astrometric measurements (4-microarcsecond wide-angle accuracy down to 20th magnitude) on target lists selected to probe questions in stellar astrophysics, Galactic structure, and the detection of planets. Survey missions, such as the European Space Agency's Hipparcos and the proposed Global Astrometric Interferometer for Astrophysics (GAIA) mission, cover the whole sky to a certain level of precision, and all science is derived from the resulting catalog. As a pointed instrument, SIM delivers much higher accuracy and the ability to measure very faint objects, on a set of targets selected in advance for specific research goals.

In this chapter, we present some examples from the SIM science program to illustrate the richness of opportunity that the mission will provide. These examples indeed cover a broad range of topics, but they do not exhaust the possibilities for major contributions from SIM. Serendipitous discoveries are very likely — as a direct result of the great leap in astrometric accuracy that SIM will provide.

Planet Detection

The possibility of habitable worlds outside our solar system has excited widespread public interest in the search for planets. The past decade has seen the topic of extrasolar planets transformed from speculation and science fiction to a well-grounded research area, with over a dozen examples of planets now known from radial-velocity monitoring. A major extension of the search is a cornerstone science goal for SIM.

Consider a solar-type star and a planet in a 3-AU orbit so that the orbit period matches SIM's primary mission length. If the planet in such a system has a mass similar to Jupiter's, the astrometric reflex



SIM PARALLAX COVERAGE
SIM can measure distances to 10 percent out to 25 kpc, compared with 100 pc in the current best catalog. (Artist's concept.)

signal is detectable to 1 kiloparsec. For an Earth-mass planet, the signal is detectable out to 10 parsecs. SIM will be able to find planets of a few Earth masses around the nearest stars, if they exist — a capability far beyond current or projected radial-velocity planet searches.

Fundamental Properties of Stars

Measuring fundamental stellar properties requires accurate distances. SIM will yield very precise data on nearby stars, extending the distance, and hence the variety of stellar types, for which 1 percent measurements are available. Most properties of stars are currently known to at best a precision of a few percent, and more typically 10 percent or even worse, limited mainly by uncertainties in distance. Direct parallax distances are of low accuracy except for Hipparcos parallaxes of the nearest stars. SIM's parallax measurements will be accurate to 4 microarcseconds, improving 250-fold on measurements by Hipparcos. Coupling SIM-derived fundamental properties of stars to theoretical investigations of stellar evolution will drive our understanding of the detailed physics operating in the interiors of stars.

Stellar Systems

SIM will make important contributions to the study of stellar systems on many scales. Accurate orbit and mass determinations of binaries will address a number of open questions concerning the evolution of interacting stars, which often end their lives in catastrophic supernova explosions and the formation of compact objects. Nearby stars in binaries with periods on the order of 5 years will have especially well-determined masses and luminosities.

Observations of open clusters, which comprise stars at a common distance and with similar ages, will allow further investigations of fine structure in the Hertzsprung–Russell (HR) diagram and tests of stellar evolution theory where mass is the primary free parameter. For globular clusters, SIM will provide a tenfold reduction in distance uncertainty, which in turn allows improved age determinations when combined with stellar evolution models. This work will directly test formation scenarios for our galaxy.

A number of problems in Galactic structure will be addressed by SIM. A 1-percent distance to the Galactic center, detailed geometry of the Galactic bar, the shape of the gravitational potential both in the disk and in the halo, and the form of the stellar rotation curve will all be studied to a new level of precision.

SIM will even reach outside our galaxy, by measuring the proper motions of Local Group galaxies to a precision of about 1 percent. Such data are not available now, but are a key part of Local Group dynamical models. Hence, SIM will advance our understanding of the dynamics of the Local Group, its origin, and its ultimate fate.

Diverse Astrophysical Phenomena

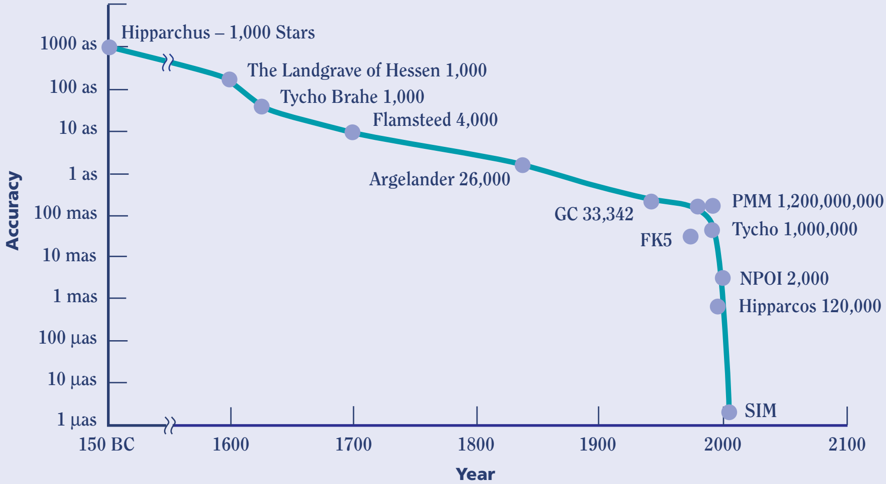
The current massive compact halo object (MACHO) event surveys rely on photometric monitoring of large numbers of stars and subsequent modeling of candidate events to determine the lens parameters. The lens mass is not derivable from photometry alone, but must be inferred through the application of models for the Galactic halo.

Astrometric observations of lensing events follow the photocentric motion of the lensed object, which does allow determination of the lens mass and distance. SIM's contribution to this field

Astrometry is truly a classical science. Its history begins with Hipparchus (150 BC), who measured 1,000 stars at 1,000-arcsecond accuracy. Progress through the centuries was slow, but the last decade has seen a dramatic change. Currently, the most accurate optical positional observations are those from ESA's Hipparcos mission. The Hipparcos catalog obtained positions at milliarcsecond accuracy for 120,000 stars down to 9th magnitude, and less-accurate positions down to 12th magnitude — a two-orders-of-magnitude improvement in astrometric accuracy. In the next decade, SIM promises improvement of over two additional orders of magnitude. The opportunities that will be opened up by SIM are only now being fully appreciated by astronomers.

Ground-Based Astrometry Using Imaging

The era of modern astrometry begins with the use of photographic plates. Schmidt plates covering the entire sky from 14th to 20th magnitude have been measured to provide stellar positions at the plate epochs to about 200-milliarcsecond accuracy for about 50 million stars; for example, the U.S. Naval Observatory (USNO) A2.0 catalog.



History of Astrometry. *Astrometric accuracy has improved over time, but slowly. SIM promises a dramatic improvement.*

Ground-based telescopes with CCD detectors can now observe with accuracies of about 25 milliarcseconds. A complete sky survey, the USNO CCD Astrographic Catalog, is now under way to extend the Hipparcos system to 16th magnitude. The Sloan Digital Sky Survey (SDSS) is observing the northern Galactic cap in five colors, achieving astrometric accuracies of 100 milliarcseconds for all stars in the 16th to 23rd magnitude range. The 2-Micron All-Sky Survey (2MASS), also under way, will cover the sky to 16th magnitude in the near-infrared, with positions better than 0.1 arcsecond.

Over narrow fields of view, a new generation of imaging instruments is achieving impressive improvements in relative astrometry (over a very narrow field). For instance, two new instruments — the Multichannel Astrometric Photometer with Spectrograph (MAPS) and the Stellar Planetary Survey (STEPS) — have both demonstrated the potential for relative astrometry at a level that is expected to yield positions much less than 100 microarcseconds in one night.

Interferometers

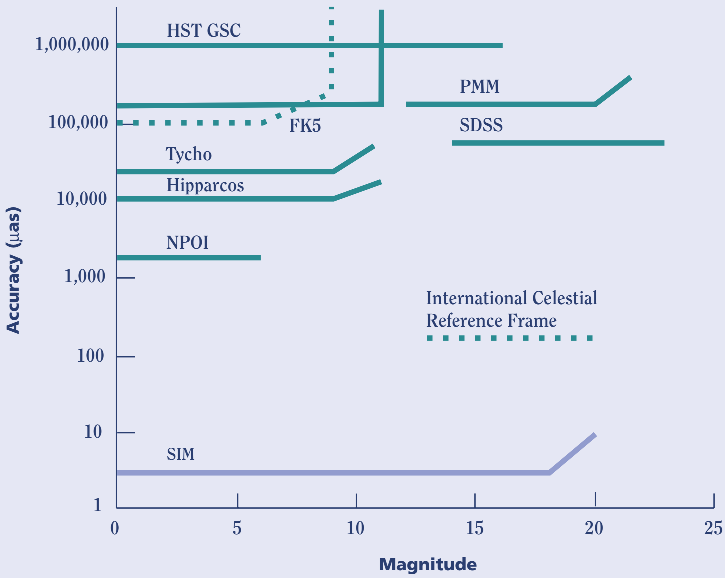
A number of ground-based interferometers for astrometry are coming on line. The Navy Prototype Optical Interferometer (NPOI) is designed for wide-angle astrometry, with an accuracy of around 1 milliarcsecond, but limited to about 9th magnitude. Other instruments include the Palomar Testbed Interferometer, the Center for High Angular Resolution Astronomy (CHARA) array on Mt. Wilson, and the Keck Interferometer. These will be capable of narrow-angle accuracy (over very small fields — the isoplanatic patch) at the 0.1-milliarcsecond level.

The accuracy of ground-based observations is limited by the atmospheric effects over both wide and narrow fields. To reach fainter sources at higher positional accuracy, especially over wide angles, optical interferometry must move to space. SIM offers the promise of 4 microarcseconds for over 20,000 stars. This represents a four-orders-of-magnitude improvement in 25 years. In addition to the revolutionary changes in accuracy of bright-star positions, there is also tremendous improvement in the accuracy and information for a large quantity of stars at magnitudes down to 20 over the entire sky.

Space-Based Astrometric Surveys

The Hipparcos project has brought about a rejuvenation of the field of astrometry, and the intense interest that its new catalog has generated underscores the importance of astrometric observations. The Hipparcos catalog comprises 118,000 stars with positional accuracies of a milliarcsecond, proper motions of a milliarcsecond per year, and parallaxes of about 1 milliarcsecond for about 30,000 stars.

The Hubble Space Telescope was not designed for the primary purpose of astrometric observations, and its primary mirror problem further restricted its capabilities. However, both the fine-guidance sensors and the Wide-Field and Planetary Camera have been used to determine relative motions and the detection of binary stars. These observations are at the accuracy of a few milliarcseconds, and have been used for as yet unsuccessful searches for substellar companions of the nearest stars.



Performance Comparisons. *Astrometric performance as a function of stellar magnitude.*

There are a number of astrometric survey missions proposed for the future. All these missions are based on the Hipparcos concept — a scanning instrument performing a sky survey and analyzing star positions from moving images in the focal plane. The Full-sky Astrometric Mapping Explorer (FAME) is planned as a full-sky survey mission. It is similar to Hipparcos but uses CCD detectors and includes four filters in the SDSS bands for photometry, with positions to 200 microarcseconds at 15th magnitude. ESA is currently studying the Global Astrometric Interferometer for Astrophysics (GAIA) concept, one of several in competition for a possible launch in 2008. GAIA would be a scanning survey mission, like Hipparcos, but with an accuracy of about 10 microarcseconds at 15th magnitude. Also under study is DIVA, a German proposal for astrometric and photometric observations to about 100-microarcsecond accuracy.

SIM Is the Next Step for Astrometry

All these space projects are surveys, based on the Hipparcos sky-survey concept. None of the missions are currently funded beyond the study-concept phase. There is a wealth of science to be derived from astrometric surveys (like those mentioned above) with well-defined completeness limits. But there are also major limitations. Sensitivity limits, the number of observations, and astrometric accuracy are all rigidly defined by the instrument architecture. For instance, observing transient events or other "targets of opportunity" is impossible; useful data can be collected only if the phenomenon happens to match the instrument's observing timeline. Perhaps the greatest limitation is sensitivity. A scanning survey devotes the same time to every object, regardless of brightness. Faint targets may be intrinsically interesting, but their astrometric accuracy is limited.

SIM is a pointed instrument, and it therefore offers the opportunity to address a completely different set of scientific questions. Most significant is its ability to observe very faint objects at high levels of accuracy — 4 microarcseconds at 20th magnitude. Some of the most demanding science requires observations of a limited number of these faint objects. Therefore, the science that SIM will do is qualitatively different — it will observe, to greater accuracy, a smaller number of targets, most of which will be selected and characterized before launch.

will be to characterize unambiguously the kinds of objects causing the observed lensing events.

The large-scale distribution of matter has been explored by galaxy surveys, and more recently through the dynamics inferred from peculiar motions of galaxies relative to the uniform Hubble flow. Knowledge of these motions is currently confined to the radial direction. SIM offers two improvements in this area. Advances in distance determination will reduce the uncertainties in peculiar radial velocities. Additionally, for galaxies with sufficiently bright central point sources, SIM will begin to measure transverse motions at the 1,000-kilometer-per-second level out to 100 megaparsecs.

SIM offers the prospect of astrometric accuracy that is more than 100 times better than that currently available.

Fundamental Physics

During its 5-year mission, SIM will establish an empirical inertial reference frame with a vector velocity that is constant to 4 millimeters per second. This is sufficiently close to inertial to detect the acceleration of the solar system by the Galactic center at the 10-sigma level.

Since SIM operates within the gravitational potential of the solar system, general relativistic effects will be present. Simple light deflection by the Sun has a typical amplitude of 1 milliarcsecond for SIM targets, sufficiently large compared to SIM's expected accuracy that useful constraints on post-Newtonian gauge parameters will be determined. For example, the gamma parameter will be measured to a few parts per million, a 1-1/2 order-of-magnitude improvement over the current state of the art.

It has been historically the case that unexpected discoveries are often made with improved instruments — a factor of 10 in a key parameter is considered a major advance. SIM offers the prospect of astrometric accuracy that is *more than 100 times* better than that currently available, so it is almost inevitable that SIM will do exciting science that is not yet anticipated — and therefore does not appear in this book.

Highlights from the Science Program

Below we illustrate the breadth of the SIM science program by describing a few science topics in some detail. SIM will make major contributions to our understanding of a range of astrophysical phenomena. The research topics that are eventually selected for the SIM science program will be the product of several proposal and peer review cycles. Opportunities to use SIM's capabilities in novel investigations will be supported through a Guest Observer Program. We invite readers to think of innovative ways to use this new astrometric tool.

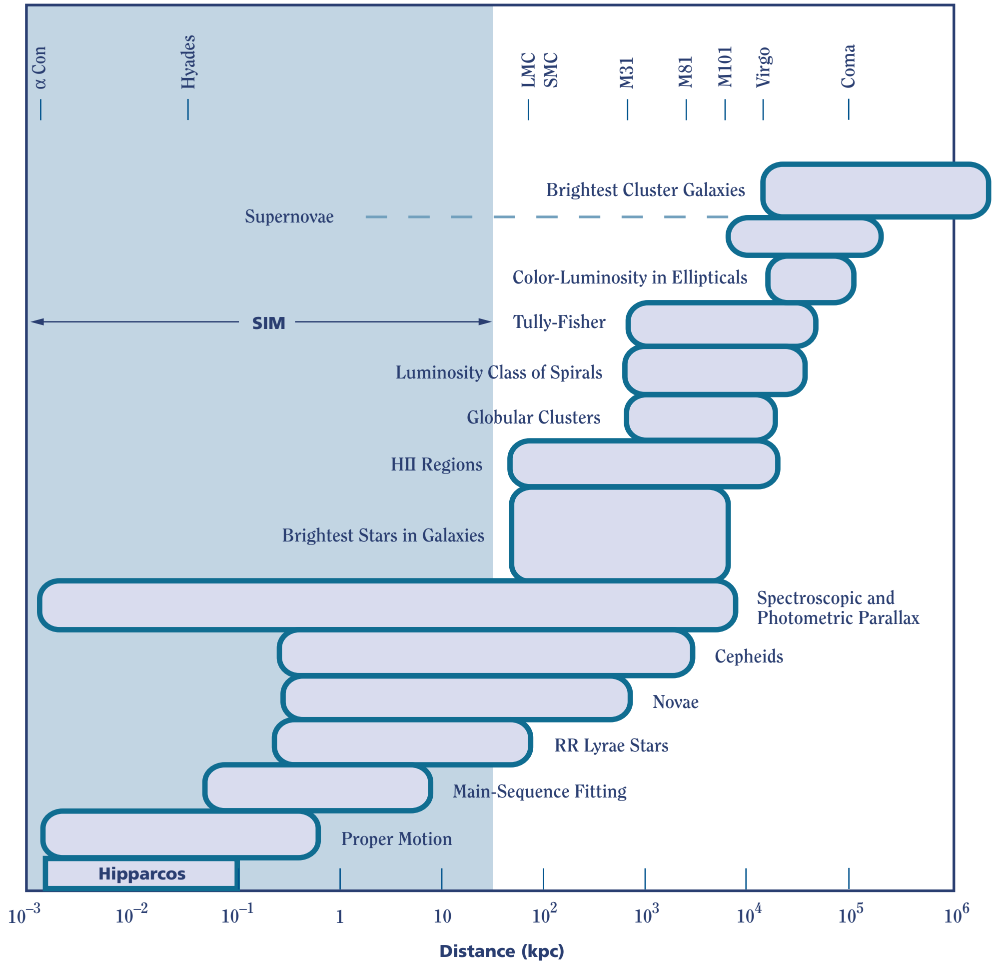
One science topic of major importance is the search for extrasolar planets. Long a subject for myth and speculation, this subject now has a secure observational foundation. It is now recognized for its importance as part of the process of star formation — a full understanding must include a viable theory of planet formation. Of course, this topic has long captured the imagination of amateur astronomers and the general public, so it is appropriate to devote a separate chapter, "The Quest for Extrasolar Planets," to exploring this exciting science in more detail.

Calibration of Distance Indicators

How big is the universe? How fast is it expanding? How old is it? How is mass distributed on a large scale? The answers to these fundamental questions rely on accurate distance measurements to galaxies far enough away that their velocities are determined mainly by the Hubble flow. These measurements, in turn, depend on accurate calibrations of standard candles and standard rulers in those galaxies. Currently, these calibrations are known to at best 10 percent, while the fundamental observables of galaxies, i.e., redshifts and apparent brightnesses of constituents, are known to much higher fidelity. Differences in interpreting cosmological models reside in that 10-percent uncertainty.

Distances to Galactic Cepheids represent the first step of the extragalactic distance scale. Uncertainties here propagate outward, limiting the potential accuracies of distance measurements at cosmological distances. SIM will enable a major improvement in the extragalactic distance scale for the same reason — improvements in Galactic Cepheid calibration from the current 10–percent level to below 1 percent will improve the accuracy of all subsequent steps in the distance scale. A secure foundation on the kiloparsec scale will provide the motivation for further improvement of distance indicators for larger scales.

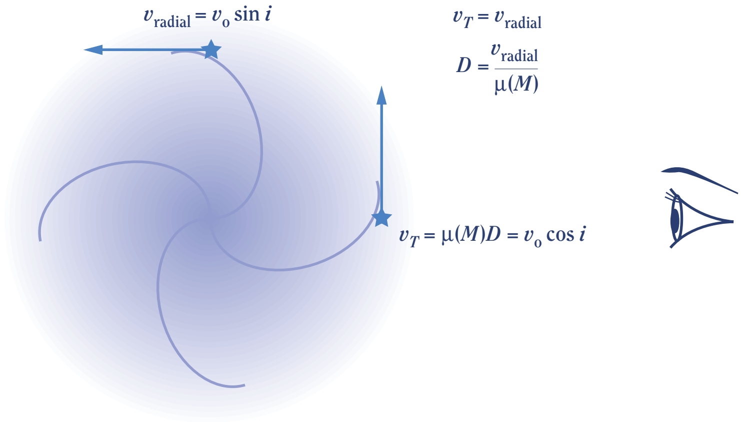
Parallax distances are completely unambiguous, and with typical distances of 1–4 kiloparsecs for Galactic Cepheids, SIM will determine their distances to 1 percent. For the first time, a Cepheid period–absolute magnitude diagram will be available, limited not by uncertainties in the distances but by such as issues as uncertainty in extinction corrections to the absolute magnitudes. Accurate near-infrared photometry minimizes extinction's effects; thus, one can expect to make progress on the question of whether the period–absolute magnitude relation is dependent on other parameters such as metallicity. Such parameters, when taken into account, can further improve use of Galactic Cepheids as distance calibrators.



DISTANCE LADDER
Distance measurements rely on calibrations of standard candles and standard rulers.

Rotational Parallaxes of Nearby Spiral Galaxies

SIM will measure distances to the nearest spiral galaxies directly, using a unique capability termed "rotational parallax," by analogy with orbital parallax. It is an important science goal for SIM because it enables an elegant and direct method of distance determination independent of all intermediate distance indicators, such as Cepheids or RR Lyrae stars. This method will be capable of precise distance measurements for the nearest spiral galaxies with uncertainties at the few-percent level. Because SIM will directly measure these distances, it eliminates potential major uncertainties due



ROTATIONAL PARALLAX

SIM measures proper motions of stars on either side of the nucleus of a galaxy. Ground-based radial-velocity measurements give the rotation velocity (after correcting for disk inclination). The ratio of these two quantities yields the distance to the galaxy directly, in a single step. (Simplified illustration.)

to luminosity-based distance indicators. SIM will provide a direct calibration of the Tully–Fisher relation used to measure larger distances in the universe.

SIM directly measures the proper motion of stars in the disks of intermediate to late-type spiral galaxies. The dominant motion of disk stars is that of rotation about the center of the galaxy, which SIM measures as proper motion. The measurement of proper motions of individual stars at several locations in the disk of a spiral galaxy, when combined with ground-based radial-velocity measurements, provides an independent measurement of the rotation curve at each location and the inclination of the disk. The distance is simply the ratio of the rotational velocity to the minor-axis proper motion.

The goal is to obtain measurements of rotational parallaxes to every large spiral galaxy with individual Population I stars bright enough to be within SIM's observing limit. With a magnitude limit of $V = 20$, all the galaxies in the accompanying table (see next page) should be observable.

Accurate distance measurements to nearby galaxies are important for other reasons. Distances allow luminosity calibrations of bright Population I objects in a variety of external systems, including the full range of Cepheids and RR Lyrae stars observable in nearby spiral systems. Precise distances will also be also important in comparing stellar populations in different galaxies.

For the nearest spiral galaxies, the desired signal is relatively large for SIM. For example, in the Andromeda galaxy (M31), a transverse velocity of 200 kilometers per second yields a proper motion of about 70 microarcseconds per

NGC	MESSIER	TYPE	i (deg)	D (Mpc)	W(20)* km/s	μ(M)† μas/yr	μ(m)‡ μas/yr	V (M_V= –8.5)
55		Sc	84	2.0	196	1	10	18.0
224	M31	Sb	77	0.77	533	16	75	16.0
247		Sc	76	2.2	220	3	11	18.2
253		Sc	81	3.0	434	3	16	18.9
300		Sc	44	2.2	163	8	11	18.2
598	M33	Sc	56	0.84	192	16	29	16.1
3031	M81	Sb	57	3.6	455	10	18	19.3
7793		Sd	47	4.1	193	5	7	19.6

* Full neutral hydrogen velocity width at 20-percent level
† Proper motion along major axis
‡ Annual proper motion along minor axis

OBSERVABLE GALAXIES

Late-type galaxies appropriate for rotational parallax measurements.

year. Combining the proper motions with a deprojected velocity map of the galaxy obtained from 21-centimeter neutral hydrogen mapping allows the distance to be measured to about 2 percent.

The ideal galaxy is one viewed at an inclination of 45 degrees (so that there is a significance in both the proper motions' modulations and the radial velocities). Nearly edge-on systems can also be used, but the inclinations, which enter weakly, will have to be estimated using other means. Face-on systems will be limited by the accuracy of the radial velocities. All these galaxies except M31 and possibly M33 can be observed by SIM in its narrow-angle operating mode (since it is differences in proper motions across the systems that are critical).

SIM will measure the distances to each of these galaxies to the limits set by systematic errors in either radial-velocity measurements (taken to be 10 kilometers per second) or in the proper motions. For the closer systems, this is easily accomplished; for M31 and M33, the process can be made wholly self-consistent, thereby avoiding as many systematic errors as possible. To do this, SIM will need to determine the velocity curve through a range of radial distances as well as solve for the other parameters. Some averaging is required to remove peculiar motions of the individual stars and any systematic perturbations to the motions due to warping of the disks and the presence of spiral arm structure. For these two nearby systems, one would observe about 25 bright members in each quadrant over the range of distances where the rotation curve is nominally constant. For the more distant spirals, a total of about 25 stars, selected with guidance from existing rotation curves, should suffice to identify "runaway" and other anomalous objects and achieve solutions accurate to 5 percent in distance (10 percent in magnitude).

Transverse Proper Motions

A "byproduct" of the rotational parallax measurement program will be very accurate proper motions for centers of mass of these same galaxies, derived from the same proper-motion data. Because these measurements will all be tied to the SIM astrometric grid, velocities derived in this way can be used to study the three-space velocities of nearby systems. The expected accuracy of around 1 microarcsecond per year corresponds to a velocity accuracy of 20 kilometers per second at the distance of M81 (3.6 megaparsecs).

Dynamics of the Local Universe

Dynamical studies of the Local Group of galaxies provide SIM with a means of probing the mass distribution and the development of structure in a galaxy group on 1-megaparsec scales. Numerous investigations of Local Group kinematics using radial velocities and distances have been conducted; Kahn and Woltjer's study in particular provided the first evidence for large amounts of dark mass in the Galaxy and in M31.

SIM will enhance the power of these studies by providing, for the first time, proper motions for a number of galaxies in the Local Group. When combined with ground-based radial-velocity data, all six phase-space coordinates of the Galaxy (position and velocity) will be known. These measurements, combined with the age of the universe and constraints from linear-perturbation theory, strongly overdetermine the orbit for a given mass distribution.

Stellar Dynamics of the Galaxy

Apart from nearby satellites of our own Galaxy, the most promising candidates include M31, M33, NGC 6822, IC 1613, WLM, and IC 10. For the nearest spiral galaxies, proper motions will be provided as a byproduct of the rotational-parallax program described above. For those galaxies, very accurate distances will further constrain models of the mass distribution. There are over 200 known galaxies outside the Local Group but within 5 megaparsecs. If, as most cosmologists assume, the peculiar velocities of these galaxies relative to the Hubble flow arise from gravitational instability, the galaxies reflect the initial perturbation spectrum and the distribution of mass in the universe.

SIM can address many outstanding problems in Galactic dynamics via accurate astrometry.

Proper motions are much more powerful probes of structure development than radial velocities because they are orthogonal to the Hubble expansion. A typical peculiar velocity of 100 kilometers per second corresponds to 4 microarcseconds per year at 5 megaparsecs. Many of the nearby galaxies are clustered into groups. The main groups within 5 megaparsecs include IC 342, M81, NGC 4244, Cen A, and Sculptor; SIM will concentrate on the Sculptor group at roughly 2 megaparsecs. The dynamics of virialized groups can be used to probe the distribution of dark matter; the principal limitation to analyses of this kind is that redshift provides only one of the three velocity components of each galaxy. By measuring proper motions, SIM can determine the other two velocity components and thereby dramatically enhance our understanding of the orbits and masses in nearby groups. A goal for SIM is the measurement of proper motions of galaxies at 2 megaparsecs to an accuracy of ±10 kilometers per second; this in turn requires a proper-motion accuracy of 1 microarcsecond per year at $V = 18.5$, the visual magnitude of a late A- or F-type supergiant at this distance.

Much of the structure of the Milky Way has been mapped — the disk, central bulge, and extended surrounding halo — but astronomers still face the fundamental questions of understanding the mass distribution and dynamics of our galaxy. Measuring the size of the Galaxy, mapping its rate of rotation, and determining how mass is distributed among its components are classical problems in astronomy, and are challenging because they are interrelated.

Among these many questions, some of the more important include: What is the size of the Galaxy? What is the distribution of mass in our galaxy, both visible and dark? What are the kinematics of stars in the outer halo as well as in and near the Galactic plane? Answers to these questions reveal much about the nature of the dark matter and the formation history of the Galaxy.

How can SIM contribute? SIM can measure the velocities and positions of stars throughout the Galactic disk (except for regions obscured by dust) and in most of the inner Galactic halo, and address many outstanding problems in Galactic dynamics via accurate astrometry. SIM will study samples of stars which serve as “tracers” of the mass distribution. Its unprecedented ability to measure stellar velocities, even at great distances, allows it to probe the Galactic potential on large scales. At a distance of 10 kiloparsecs, transverse velocities can be measured to 1 kilometer per second, and distances to 5 percent, over the 5-year mission lifetime. Many of the more distant stars are very faint, so SIM's ability to maintain accurate astrometry down to $V = 20$ is essential for some of this work.

Mass of the Galaxy

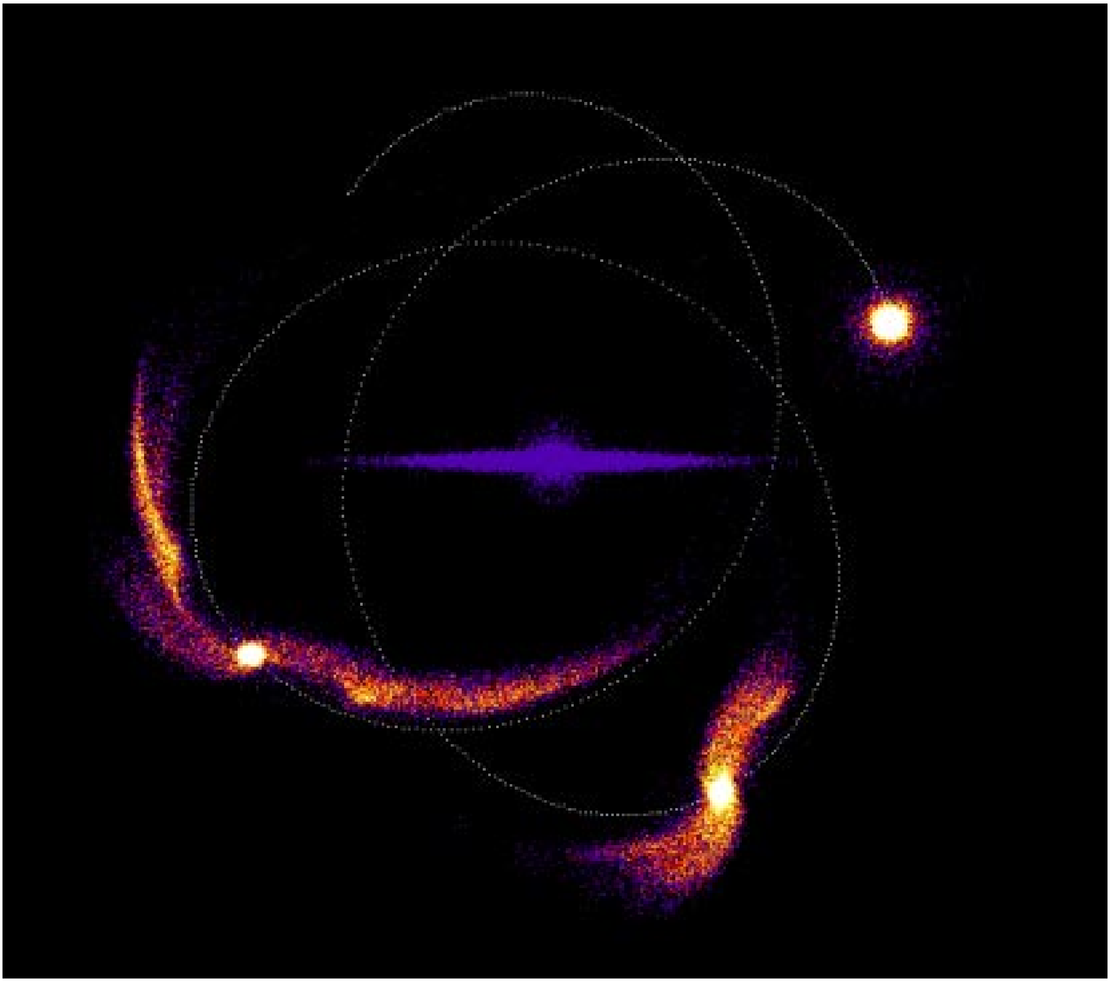
SIM's 4-milliarcsecond astrometric accuracy will allow us to measure distances to 5 percent at 10 kiloparsecs for stars with $V < 20$, giving us insight into the potential of the outer halo. SIM can use a sample of bright late-type stars to trace the Galactic potential, and hence, the mass distribution. Specifically, the potential is determined by using the classic Jeans equations analysis, which relates the spatial density of stars, the mean stellar velocity, and the gravitational potential, via differential equations.

Comparing the observed rotational speed of stars with the amount of mass traced by stars and dust indicates that there is a vast amount of unseen, or dark matter. Tracing the distribution of the Galaxy's mass becomes difficult at galactocentric distances beyond the Sun's orbit — where the Galactic rotation curve is not well defined — currently relying on data sets possessing considerable uncertainty in distance (and hence, in rotation velocity). The origins of the Galactic halo are also uncertain — did its constituent stars form early in Galactic history, or are they continually tidally stripped from infalling satellites?

Galactic potential observations can also be used in determining the relationship between metallicity and Galactic orbit for a large population of halo stars to infer the Galaxy formation history. In this instance, SIM will be limited by its ability to measure parallax, and will therefore focus on stars lying within 10 kiloparsecs of the Sun. Obtaining accurate orbits for at least 400 halo stars would allow us to detect a 10-percent variation in velocity dispersion with metallicity.

Tidal Streamers in the Outer Galaxy

In the outer Galaxy, tidal streamer stars are used to trace the potential. By exploiting the fact that these stars lie along a single orbit, the Galactic gravitational potential in the outer Galaxy can be measured to an accuracy of a few percent. This technique requires proper motions and ground-based radial velocities (obtained separately), but does not require parallaxes. The distribution of a tracer population in the halo can yield the distance to the Galactic center R_0, while debris from a recent or ongoing passage of an infalling satellite galaxy will present a phase-space distribution signature.



TIDAL STREAMERS
Disruption of a dwarf spheroidal galaxy by the Milky Way.
(K. Johnston, Inst. for Advanced Study)

Moving Groups

Candidates include the tidal tails of the Large and Small Magellanic Clouds, Sagittarius, Fornax, Leo I, and Leo II. Recent work has traced tidal tails in the first two systems. It is likely that tidal-tail stars will be found for the other systems over the next few years. With five systems, measuring 5-dimensional phase-space information for 100 stars in each tidal tail, SIM will be able to measure the Galactic mass profile as a function of radius with an accuracy of better than 5 percent. These observations will also measure the shape of the Galactic potential. This project will require prelaunch surveys to identify candidate objects.

SIM

Our Milky Way is a dynamic place — the “fixed stars” are anything but fixed. For SIM, every star it measures is a moving target and must be characterized by the five classic astrometric parameters:

• Position (RA and Dec) • Proper motion (in RA and Dec) • Parallax

The only exceptions to this rule are stars in nearby galaxies, for which the parallax is too small to be detectable by SIM. To adjust to the scale of precision in these quantities which SIM represents, consider the following benchmarks:

- Velocity accuracy (in the plane of the sky) at the nearest stars — 1 centimeter per second
- Position accuracy (in the plane of the sky) at nearest stars —1,000 kilometers
- Parallax distance accuracy at 10 parsecs — 0.004 percent
- Parallax distance accuracy on the far side of Galactic disk — 5 percent
- Velocity accuracy on the far side of Galactic disk — 200 meters per second

These capabilities open up new scientific opportunities across a number of disciplines in astrophysics. The science topics in this chapter represent some of the science that can be done with astrometric data at this level of precision.

Close Stars

SIM’s positional accuracy will allow the detection of a planetary companion of an Earth mass via its gravitational pull on the parent star. Orbit parameters of binary stars can be determined to very high precision, allowing accurate measurements of masses in many systems for the first time. SIM’s astrometric method eliminates the uncertainty in orbit inclination that limits the radial velocity method.

Distant Stars

With SIM’s precision, stars anywhere in the disk and the halo of our galaxy can be followed as probes of Galactic structure. With the addition of ground-based radial velocities (from high-resolution spectroscopy), each SIM star will have a full 6-D position in physical and velocity space, essential for a full understanding of the Galactic mass distribution.

Galactic Rotation

The Galactic rotation curve is flat or slightly rising for the outer Galaxy, changing slowly with distance. Establishing an accurate rotation curve (and hence, an accurate measurement of radial mass distribution) calls for very precise tangential velocities and distance measurements. SIM's parallax errors could yield velocities on the far side of the Galaxy to 20-percent accuracy.

A definitive determination of the Galaxy rotation law requires careful sampling of the kinematics throughout the plane of the Galaxy. It is important to follow the stellar kinematics well above the plane if the full vertical distribution of gravitating matter is to be sampled. Using tracers to find the integrated surface density has given a range of possible values, with corresponding uncertainty in the dark-matter population. SIM will be able to extend the extent of sampling significantly out of the plane, constraining the overall density range.

A relatively small number of stars may be available far from the plane. Perhaps 100 objects will be necessary to define the basic outlines of the velocity distribution at each level, spacing each group of objects approximately 5 kiloparsecs apart. With little reddening and $M_V = 0.0$ for the typical K giant targets, the objects are $V = 16.5$ and brighter; derived velocities will again be limited in accuracy by the parallaxes.

The Galactic Bar

In the inner Galaxy, SIM can determine the width and orientation of the bar by determining the median distance to stars along three lines of sight. Views of the Galactic center in optical wavelengths are restricted to a few regions of low interstellar absorption. By measuring the distances to stars in Baade's window, SIM can determine the Sun's galactocentric distance R_0 with an uncertainty of 1 kpc/$\sqrt{N}$, where 1 kiloparsec is the width of the bar at Baade's window and N is the number of stars observed. By determining astrometric distances to red clump stars in the Galactic bulge, these stars can be used as calibrators to trace the size and shape of the Galactic bar. Alternatively, astrometric distances can be obtained directly and then used to determine the bar width and angle. With 50 stars along each line of sight, SIM should be able to determine R_0 with an accuracy of 3 percent. These stars can then be used as distance calibrators throughout the bar.

Microlensing

Gravitational microlensing — the bending of light from a distant star by chance passage close to another star along the line of sight — can be used to study the population of MACHOs in the Galaxy.

In particular, the MACHOs studied through *photometric* signatures may be a significant component of the dark matter thought by dynamical considerations to exist in the Galaxy. SIM will make a major contribution to this research by providing lens masses directly — through the *astrometric* signature of microlensing. Photometric events yield masses only through a number of assumptions, including a mass model for the Galactic halo.

Bohdan Paczynski first suggested photometric observations of microlensing in 1986, and in the past several years Paczynski's suggestion has been confirmed, with several groups reporting significant numbers of candidate gravitational microlensing events from photometric observations of Large Magellanic Cloud (LMC), Small Magellanic Cloud (SMC), and Galactic bulge sources. The large majority of light curves for these microlensing events match theoretical expectations for single lens objects, and all collaborations report a significant excess of microlensing-event candidates above the number expected from known stellar populations. Microlensing observations have already shown that a considerable part — possibly more than half — of the dark matter in the Galactic halo consists of objects with a mass spectrum ranging from 0.05 to 0.8 $M_{\odot}$.

A difficulty in interpreting the photometric events is that they cannot determine the mass of the lens itself. Instead, the conclusions rely on interpreting event sample observables (namely, event duration) in the context of a halo model. However, other interpretations are possible, and it is desirable to derive physical properties in a model-free context. There are several hypotheses concerning the nature of these objects. They could be baryonic matter in the form of Jupiter-mass planets or small stars (brown and white dwarfs). Or they could be noncompact objects — small-scale formations occurring in nonbaryonic dark matter. By measuring lens masses directly, SIM may help to decide this question.

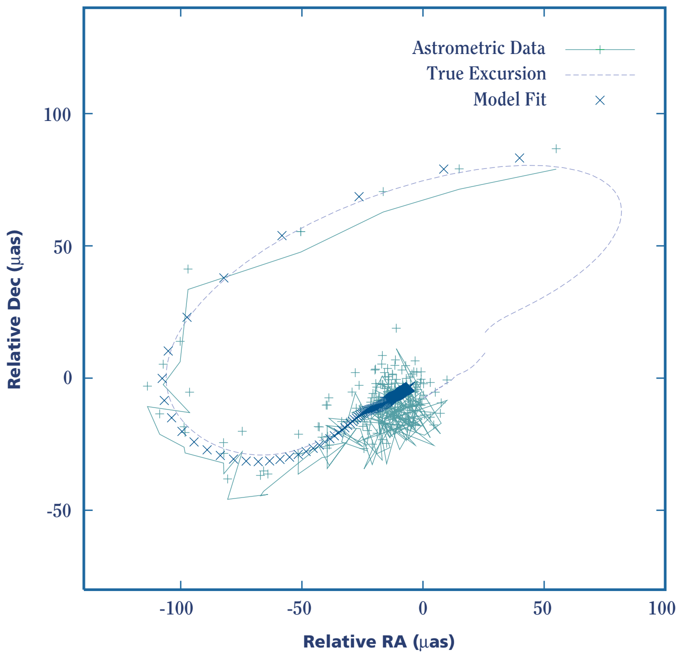
These questions provide a strong motivation for astrometric observation of MACHO gravitational microlensing events. High-precision astrometric observation of such microlensing events allows the estimation of the lens parameters (mass, distance, proper motion) appealing only to the properties of the lensing process. The figure on the next page is a numerical simulation of an astrometric signature of a microlensing event in the LMC, and assumes 3-percent photometry and 10-microarcsecond differential astrometry referenced to the unlensed source position. The lens has a mass of 0.1 $M_{\odot}$ and is in the Galactic halo at a distance of 8 kiloparsecs.

SIM is unlike any other astrometric instrument. Continuous scanning space-based instruments, such as the ESA Hipparcos mission, are basically imaging devices that measure wide angles simultaneously between stars on the detectors. SIM is a Michelson interferometer; its heritage can be traced from ground-based interferometers such as the Mark III interferometer on Mt. Wilson and the Palomar Testbed Interferometer.

Unlike a ground-based interferometer, which uses a well-defined baseline fixed to the rotating Earth, SIM measures objects serially with a single interferometric baseline vector, whose length and orientation are not known *a priori* to sufficient precision by any direct measurement. For each observation, the instrument is held (approximately) inertially stable while starlight is collected and metrology measurements are made. The fundamental observable is the internal delay required to equalize the starlight pathlengths in the two interferometer arms as measured by an internal laser metrology system.

During the measurement set, two guide interferometers observe bright stars and a third interferometer collects science data. Data from the guide interferometers are combined with the "science data" in ground processing to derive a "regularized baseline" — the equivalent of a perfectly stabilized instrument. The guide interferometers follow any drift in the baseline vector with time, at a level of precision at least equal to that of the desired science measurement. This eliminates the requirement for actual instrument stability at the microarcsecond level (equivalent to hundreds of picometers).

To minimize systematic errors, the measured delays used in astrometric reductions are taken from just one single interferometer. In this model, SIM does not directly measure the relative angle between objects in the sky. Instead, SIM measures delays to multiple objects that are interrelated via knowledge of the interferometer baseline vector and its evolution in time. This time-evolution knowledge of the baseline attitude is provided by the guide interferometers.



MICROLENSING IN THE LMC

Numerical simulation of the astrometric signature of a microlensing event in the Large Magellanic Cloud.

Simulations show that SIM will be able to measure the key lens parameters. SIM would observe in a target-of-opportunity mode, with targets selected on photometric microlensing events in progress, discovered by ground-based monitoring. A parametric microlensing model fit to the combined (astrometric and photometric) data sets reproduces the measurements faithfully and predicts the microlensing parameters accurately. In particular, sufficient accuracy on the angular Einstein radius and relative parallax parameters is observed to establish the lens mass and distance to approximately 15 percent. Such an estimate of the lens distance would unequivocally distinguish whether the lens is in the Galactic disk, halo, or in the Large Magellanic Cloud itself.

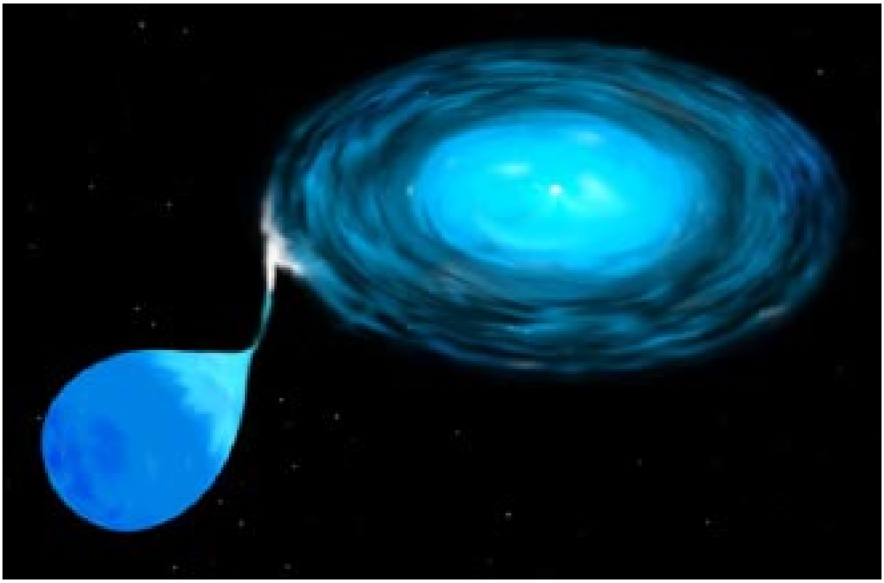
Masses of Cepheid Pulsators

A specific example of a stellar evolution question is the mass of Cepheid variables. For Cepheids in binary systems such as V636 Sco, SIM can provide a mass estimate to better than 1 percent.

An accurate Cepheid mass allows stellar theorists to compare their pulsation models against the actual pulsations taking place in the outer regions of a star of known mass, luminosity, and radius. An accurate estimate of the mass of a Ceph-

CLOSE BINARIES

Artist's concept of a white dwarf star disrupting a main-sequence companion. (Courtesy of Space Telescope Science Institute.)



eid also establishes accurate empirical points in the Cepheid mass–luminosity relation. Such studies, in turn, bear on the question of intrinsic spread in the Cepheid period–luminosity relation, which is fundamental to calibrating extragalactic distances.

In the V636 Sco binary system, the Cepheid is a companion to a B9.5V star (Vega-like) secondary. The current state of the art in direct mass measurements comes from Hubble Space Telescope radial-velocity studies, which yield a mass of 3.1 ±0.4 $M_\odot$ for the Cepheid. With a 1-percent mass estimate, SIM will clearly make a major impact on our ability to test physical models of these stars.

Exploring the Hydrogen-Burning Limit

Another example from the SIM science program is that of determining the precise mass of the hydrogen-burning limit, below which lie the brown dwarfs and giant planets. Several substellar and nearly substellar objects are in binaries. SIM astrometry at the microarcsecond level will establish the parallax and orbit of the systems — and hence masses — to high accuracy. Observations of a number of such binaries have the potential to find the hydrogen-burning limit; the accuracy to which it can be obtained is likely to be limited most by the availability of systems straddling the boundary. One relatively close system is GD 165B, discovered by Becklin and Zuckerman. It

One of the most important products of the SIM astrometric campaign will be the high-precision optical reference frame. SIM will define a reference frame whose internal accuracy of 4 microarcseconds vastly exceeds that of existing catalogs. This frame will significantly improve the quality of the extragalactic reference frame that is currently used for deep space navigation, Earth-orientation measurements, geodesy, and astrometry.

Celestial reference frames have been used for millennia to measure the passage of time, for navigation, and for studying the dynamics of the solar system. In the last century, these frames have become important for studying the dynamics of more distant objects and geophysical phenomena on Earth. The consequent increase in the level of accuracy of celestial reference frames — from roughly 0.1 arcsecond using optical telescopes to the submilliarcsecond level via very long baseline interferometry (VLBI) — has permitted unprecedented studies of celestial dynamics and geophysical phenomena. However, stellar reference frames are time dependent because stars exhibit detectable motions. For precise astrometric applications, a stellar frame must specify, in addition to positions, an epoch and predicted stellar motions. Imprecise knowledge of proper motion and/or parallax limits the precision of stellar frames at epochs other than the catalog mean epoch. Extragalactic radio sources, on the other hand, are assumed to be very distant (with typical redshifts of about 1.0), and thus should exhibit little or no detectable motion. A reference frame defined by the positions of extragalactic radio sources may be said to be a quasi-inertial frame (i.e., nonrotating with respect to an inertial frame) with little or no time dependence. Thus, linking a highly accurate stellar reference frame to the extragalactic frame is highly desirable.

The astrometric frame adopted by the International Astronomical Union is defined based on the radio positions of 212 extragalactic sources distributed over the entire sky. Positional accuracy of these sources is better than about 1 milliarcsecond in both coordinates. Radio positions from VLBI data were used to define the International Celestial Reference Frame (ICRF); the Hipparcos catalog is used for optical wavelengths. The dynamical frame of planetary ephemerides has also been linked to the extragalactic radio frame. With these links in place, the inherent stability and accuracy of the extragalactic celestial frame is now accessible to a much wider group of astronomers and techniques.

SIM will be capable of determining a celestial reference frame of several thousand objects with a precision of 4 microarcseconds. This precision is almost two orders of magnitude better than the current state of the art in astrometry. Furthermore, given sufficiently long integration time on a source, the SIM instrument will detect extragalactic radio sources directly, a feat beyond the Hipparcos sensitivity limit. Such observations would allow direct comparison of the radio and optical celestial frames at unprecedented levels of accuracy. Since the Hipparcos source positions are degrading by ~1 milliarcsecond per year, they will have uncertainties of about 15 milliarcseconds by the time SIM is launched. Thus, the SIM optical reference frame will be able to provide the most precise anchor for the reference frames realized at the other wavelengths.

is a brown dwarf in a 120-AU orbit around a white dwarf primary. SIM can provide unprecedented accuracy of 0.1 percent in the parallax distance.

Masses and Evolution of Close Binary Stars

Since the time of Eddington, we have understood that mass is the fundamental stellar parameter. No means has yet been found to determine reliable stellar masses other than through dynamical interactions. Precision astrometry with SIM will yield stellar mass with 0.5-percent uncertainties — and from absolute binary orbit determinations, to better than 1 percent.

Except for eclipsing binaries, which are relatively uncommon, and are almost always short-period (close) systems, direct mass determinations require precision astrometry. In the classical case of a visual binary, the system mass depends on the cube of the distance, so accurate parallax is essential. Obtaining individual masses requires measurement of the absolute orbits, a prospect essentially unheard of until SIM.

The evolution of close binary stars can be very different than that of wide binaries or isolated stars. If the stars are close enough, mass is exchanged as first one star, then the other, evolves off the main sequence. In some cases, this mass exchange can lead to supernova explosions and the formation of compact objects. Understanding the details of these processes requires accurate knowledge of the initial masses and evolutionary paths of the stars. Masses and orbital parameters derived by SIM will specify a point in parameter space that any model for the system must satisfy at the observing epoch.

Knowledge of accurate masses for noninteracting binaries, where the evolution of each star is independent, is important for checking and calibrating standard stellar evolution theory against a number of parameters. Mass is the key parameter, but also important are chemical composition, the physics of mixing, stellar rotation, mass-loss parameterizations, and, for stars in clusters, stellar age.

Ages of Globular Clusters

Globular clusters have ages that are comparable to the age of the universe, and thus accurate determinations of their ages provide critical tests of cosmological models. Accurate globular cluster ages are also important for setting and interpreting the chronology of the earliest stages of star formation in our galaxy, and the formation of the Galaxy itself. These tests would be greatly strengthened if the cluster ages were better known.

Currently measured ages of the oldest globular clusters are not accurate enough to distinguish between key cosmological models, nor between key models for the formation of the Galaxy. How does one measure the age of a globular cluster? The key is having accurate stellar luminosities, which in turn implies a need for accurate distances — these can be directly provided by SIM parallaxes. Parallax measurements by SIM will determine the distance to the nearest clusters to 1 percent. Direct distance measurements are very important, because they sidestep the assumptions necessary when applying indirect methods. Thus, distances provide a calibration for the main-sequence turnoff luminosity in the observed cluster HR diagram. The final step is to match the observed HR diagram with a turnoff age versus luminosity calibration determined from stellar evolution theory.

Probing the Early History of Our Galaxy

In a summary of the current state of the art, Chaboyer and coworkers find that the best-measured globular clusters have uncertainties in their main-sequence turnoff luminosities of 0.08 magnitudes. This in turn leads to a 1.3-gigayear uncertainty in the age of a globular cluster, which is large enough to span a number of cosmological models and early galaxy-formation models. Reducing the uncertainties to around

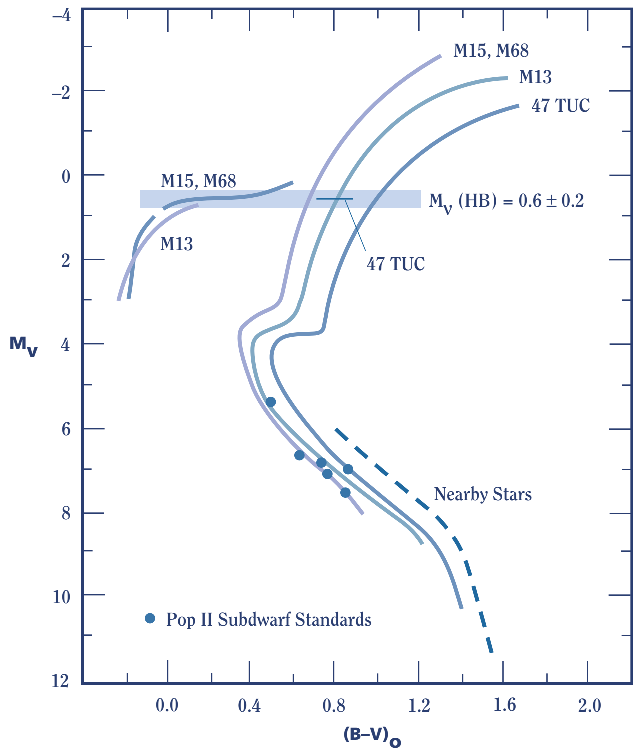
SIM will be capable of determining a celestial reference frame of several thousand objects with a precision of 4 microarcseconds.

1 percent will distinguish between competing models in both areas. For example, ages of globular clusters known to ±150 million years — roughly the dynamical timescale for the collapse of material to form the Galaxy — will tell us whether or not the Milky Way was created during such a collapse or through the aggregation of a large number of dwarf galaxies over a substantially longer time.

Estimates of the age of the universe from cosmology in different models is from 9 gigayears (if the density is critical) to 14 gigayears (empty universe). This is the same range as currently measured globular cluster ages. Firm measurements of globular cluster ages will directly constrain the possible cosmologies.

Observational Tests of General Relativity

SIM may be the first experiment to provide the high-accuracy observational data that are necessary to measure the parameterized post-Newtonian (PPN) γ



GLOBULAR CLUSTER AGES

This age sequence shows the critical parameter to determine ages of globular clusters — the turnoff point where stars evolve off the main sequence.

According to general relativity, the light rays propagating near a gravitating body will be deflected by the curvature of space–time caused by the body's gravity field. In a weak gravity-field approximation for observed sources located at large distances, the angle of deflection $\delta\alpha$ is given as $\delta\alpha \sim \frac{1}{2}(\gamma+1)\,\frac{4\,GM}{c^2 b}$ where M is the mass of the deflector and b is the impact parameter of the light ray, respectively; γ represents the measure of the curvature of the space–time created by a unit rest mass. General relativity gives $\gamma = 1$, when analyzed in standard parameterized post-Newtonian (PPN) gauge.

Measuring the Bending of Light

The bending effect is large by the standards of modern astrometry. Viewing the sky at right angles to the Sun, the apparent position of every star is shifted by 4 milliarcseconds — one thousand times SIM's accuracy! Even for Jupiter, the angle of deflection amounts to 2 microarcseconds, which is detectable by SIM over large parts of the sky. The effects are large enough that the Hipparcos catalog (0.6-milliarcsecond precision) had to allow for bending due to the Sun. With more than two orders of magnitude better measurement precision, the SIM astrometric grid catalog accuracy will depend on making these corrections to high precision.

Stellar Aberration

Even the special-relativity effect of stellar aberration must be carefully taken into consideration. The effect, first measured in the 18th century by Bradley, is large — a maximum of about 20 arcseconds. For the Hipparcos astrometric catalog, the stellar-aberration calculation required terms up to second order in addition to the familiar first-order term. At SIM's level of accuracy, aberration causes the measured angle between two stars in the field of view to change measurably in less than 1 second. Fortunately, this does not affect the instrument operation, but is an example of a number of subtle effects that must be allowed for in producing the all-sky grid catalog at microarcsecond accuracy.

SIM's high-accuracy data may be used to enhance our understanding of general relativity.

to a few parts in a million. This would represent a significant advance in our understanding of gravitation and test the applicability of general relativity to the strong-field regime.

In a strong gravitational field, the classical description provided by general relativity breaks down and an extension of gravitational theory is required. Deviations of the parameter γ from unity are a way of testing the validity of scalar-tensor gravitational theories. Indeed, the accuracy of many astronomical observations requires a relativistic description of light propagation as well as a relativistically correct treatment of dynamics of the extended celestial bodies of the solar system. The last two decades have seen the status of general relativity change from a mostly theoretical discipline to a science of practical importance.

SIM will provide a measurement of $|\gamma - 1|$ with a precision up to 10^{-5}–10^{-6}, as a byproduct of the astrometric grid catalog development. The best current measurements, from analysis of VLBI data, are a factor of 10 worse, around $|\gamma - 1| = 3 \times 10^{-4}$. This improvement is sufficient to take the precision into the range where the PPN approximation is significantly tested.

At SIM's level of accuracy, even more subtle effects will start to become apparent, such as the quadrupole components of the gravitational fields of the Sun and the planets, light-modulation effects due to gravitational lensing by MACHOs, and possible metric perturbations due to gravitational waves. These microlensing effects are estimated to be on the order of several microarcseconds.